AEDC-TDR-64-185

NON-CONTAMINATING COMBUSTION AIR HEATER FOR WIND TUNNELS

By

Robert O. Dietz, Jr.
DCS/Research, Hq AEDC

TECHNICAL DOCUMENTARY REPORT NO. AEDC-TDR-64-185

November 1964

ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

NOTICES

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ABSTRACT

An analysis of a wind tunnel combustion air heater that will provide uncontaminated air at temperatures above 4000°R is presented. Concept of the heater involves combustion of metals that yield oxides having melting temperatures above 4000°R. Heat is transferred to air from liquid metal-oxide particles formed in a metal-oxygen combustor. The oxide particles solidify during the heat-transfer process and are separated from the air by centrifugal forces. A portion of the heated air is bled from the periphery of the separator to carry the oxide particles out of the wind tunnel air supply system.

Thermodynamic analyses of the heater are discussed, and they show that combustion of 0.077 lb of aluminum per pound of air will provide a wind tunnel air supply temperature of 4100°R. Calculations presented show that five-micron aluminum-oxide particles can be separated from high density air using a tangential velocity of 200 ft/sec in a centrifugal separator. Experimental research needed to verify the results of the analyses and to provide design data are outlined.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

D. R. Eastman, Jr.
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NOMENCLATURE

A	Area, ft^2
C_p	Mean specific heat, Btu/lb_m-°R
d	Diameter, ft
F	Force, lb_f
g_c	Gravitational constant (32.2), $\frac{lb_m\text{-}ft^2}{lb_f\text{-}sec^2}$
H_c	Heat of combustion, Btu/lb_m
H_F	Heat of formation, Btu/gm formula weight
h	Enthalpy, Btu/lb_m
J	Mechanical equivalent of heat, $\frac{ft\text{-}lb_f}{Btu}$
k	Coefficient of thermal conductivity, $\frac{Btu}{ft\text{-}sec\text{-}°R}$
M	Formula weight
m	Mass, lb_m
Nu	Nusselt number
P	Total pressure, lb_f/ft^2
Pr	Prandtl number
p	Static pressure, lb_f/ft^2
Q	Total heat transferred from particle to air, Btu
Qi	Total heat available from particle, Btu
q	Surface heat-transfer coefficient, $\frac{Btu/ft^2}{sec\text{-}°R}$
R	Radius of rotation (4), ft
Re	Reynolds number
r	Radius, ft
S	Distance, ft
T	Temperature, °R
t	Time, sec
U	Velocity normal to radius vector and normal to duct centerline (200), ft/sec
V	Radial velocity, ft/sec

v	Specific volume, ft^3/lb_m
W	Velocity parallel to duct axis, ft/sec
w	Weight, lb_m
γ	Ratio of specific heats for air (1.374)
η	Combustion efficiency
μ	Viscosity, $\frac{lb_f\text{-sec}}{ft^2}$
ρ	Density, lb_m/ft^3

SUBSCRIPTS

Al	Aluminum
Al_2O_3	Aluminum oxide
a	Air
C	Centrifugal
D	Drag
M	Gram formula weight
O	Oxygen

1.0 INTRODUCTION

High-temperature, high-pressure air is required to provide duplication of flight conditions in high-speed wind tunnels. Total energy release rates in air heaters for large, continuous-type, high-velocity, low-altitude wind tunnels needed to test hypervelocity air-breathing engines can be as high as 2,200 mw. Indirect-fired air heaters are currently used to provide high-energy release rates in wind tunnels at air temperatures up to 1260°R (Ref. 1). Alumina and zirconia storage heaters provide air at temperatures up to 4000°R for wind tunnels that operate for less than three minutes (Refs. 2 and 3). Longer operating time with air temperatures of about 4000°R are provided through the use of combustion air heaters.

Combustion of fuel with the air that comprises the working fluid in a wind tunnel as is done in combustion air heaters depletes the oxygen content of the air. Products of combustion from hydrocarbon fuels used in combustion air heaters contaminate the air flowing through the wind tunnel. Deleterious effects of oxygen depletion and air contamination on air-breathing engine test data include unpredictable and inconsistent changes in engine burner performance and operation. This report presents a concept for a combustion air heater that will provide air temperatures in the neighborhood of 4100°R and will, to a large extent, be free of the deleterious effects of oxygen depletion and air contamination.

Results of a thermodynamic analysis of the proposed combustion air heater are discussed in this report, and they show the technical feasibility of the heater. The critical problem of separating the combustion products from the tunnel airstream is discussed. Analyses of capital costs and operating costs are discussed. Analytical and experimental research needed to provide a solution to the combustion and separation problems and to provide design data are outlined.

Interest in the test capability provided by the combustion air heater discussed in this report is significant at this time. True temperature simulation at flight Mach numbers up to eight and altitudes as low as 95,000 ft could be provided by the heater. Most of the improvement in space vehicle-booster mass ratio that can be achieved through the use of the advanced air-breathing engines is provided by the use of the air-breathing engines at flight Mach numbers below eight (Ref. 4).

Manuscript received August 1964.

2.0 DISCUSSION

2.1 CONCEPT

Combustion air heaters offer low capital costs. Current installations use developed turbojet or ramjet combustors installed in the air supply duct of the wind tunnel. Operating costs are reasonable because commercially available hydrocarbon fuels are used to provide thermal energy directly to the wind tunnel air supply without significant energy losses. Flexible wind tunnel operation is provided by the quick reaction time of the combustion air heater and the broad temperature range that a given heater can cover with relatively simple controls.

A wind tunnel air heater that could provide these advantages of the combustion air heater while avoiding its problem of air contamination might be achieved by using fuels that produce inert, liquid, or solid products of combustion. Combustion products that were completely inert might be allowed to flow through the wind tunnel test section. Liquid or solid combustion products might be separated from the tunnel working fluid by taking advantage of the differences in physical properties of the combustion products and air. Reference 5 shows ten inorganic "oxides" that have melting temperatures above 4000°R. Table 1 shows the metals, their oxide formulae, and the melting temperatures of the oxides.

Operation of a wind tunnel combustion air heater using one of the fuels shown in Table 1 with a tunnel working fluid temperature below that shown in Table 1 would produce solid oxide particles in the tunnel air supply. Oxygen enrichment of the air, perhaps in the heater itself, to make up for that consumed in the combustion air heater would provide high-temperature air of the proper composition contaminated only by solid oxide particles. The relatively high density of the oxide could be used to separate the oxide particles from the wind tunnel air supply. The concentrated oxide-air mixture could be bled off the tunnel air supply system.

2.2 THERMODYNAMIC ANALYSIS

Combustion of aluminum with oxygen is represented by the chemical formula

$$2\ Al + 1\tfrac{1}{2}\ O_2 \longrightarrow Al_2O_3$$

Atomic weight of aluminum is 26.981 or, say, 27. Atomic weight of oxygen is 16. The formula weight of aluminum oxide is

$$2\ (27) + 3\ (16) = 54 + 48 = 102$$

The heat of formation of aluminum oxide at a temperature of 524°R and a pressure of one atmosphere is 1545 Btu (gram formula weight) (Ref. 5). The heat of formation of aluminum oxide in a process in which initial conditions are 524°R and 100 atm and the final conditions are 4100°R and 100 atm is obtained by making proper corrections.

$$H_F' = H_F + v_{Al}\Delta P - v_{Al_2O_3}\Delta P - C_{p_{Al_2O_3}}\Delta T$$

$$= \frac{1545 \text{ Btu}}{102 \text{ gm}} 454 \frac{\text{gm}}{\text{lb}} + \frac{1}{167.6} \frac{(211600 - 2116)}{778} -$$

$$\frac{1}{212} \frac{(211600 - 2116)}{778} - 0.27 \ (4100 - 524)$$

$$= 5914 \text{ Btu/lb } Al_2O_3$$

A final temperature of 4100°R was selected to ensure that the aluminum oxide would be solid at the heater outlet. The heat of combustion of aluminum was determined from the heat of formation of aluminum oxide.

$$H_F\,[Al] + H_F\,[O_2] + H_c = H_F'\,[Al_2O_3]$$

$$= \sim 0 + \sim 0 + H_c = 5914 \text{ Btu/lb of } Al_2O_3$$

$$H_c = 5914 \frac{102}{54} = 11{,}170 \text{ Btu/lb of Al}$$

It was assumed that air entered the combustion air heater at a temperature of 1200°R and a pressure of 100 atm. Enthalpy required to raise the temperature of the air to 4100°R was taken from Ref. 6.

$$\Delta h = 1150 - 290 = 860 \text{ Btu/lb}$$

Aluminum that must be burned with air to raise the temperature of air from 1200 to 4100°R is

$$\frac{W_{Al}}{W_a} = \frac{\Delta h_a}{H_c} = \frac{860}{11{,}170} = 0.077 \text{ lb/lb}$$

Oxygen required is

$$\frac{W_{O_2}}{W_a} = \frac{W_{Al}}{W_a} \frac{3M_O}{2M_{Al}} = 0.0734 \frac{48}{54} = 0.0684 \text{ lb/lb}$$

Aluminum oxide in the tunnel working fluid would be

$$\frac{W_{Al_2O_3}}{W_a} = \frac{W_{Al}}{W_a} \frac{M_{Al_2O_3}}{2M_{Al}} = 0.0734 \frac{102}{54} = 0.1455 \text{ lb/lb}$$

These calculations show the quantities of aluminum and oxygen required in a wind tunnel heater using aluminum as a fuel. Amounts of aluminum oxide contamination that should be removed from the tunnel working fluid are also indicated. Thermodynamic feasibility of a combustion air heater using aluminum as a fuel is shown by the calculations.

Thermodynamic analysis of other fuels shown in Table 1 should be made except where the fuel can be readily eliminated because of other considerations. Factors that may eliminate some of the fuels from consideration include low chemical reaction rates, microscopic combustion characteristics, low availability, high cost, excessive oxide production, and macroscopic combustion characteristics.

2.3 COMBUSTION

Aluminum is chemically reactive with air and oxygen. The rate of flame movement through clouds of aluminum powder and air is of the same order of magnitude as that of hydrocarbon-air mixtures (Ref. 7). The limits of inflammability of aluminum indicate that aluminum powder mixed with air can support a flame of atmospheric temperature and pressure in fuel air ratios as lean as 12 percent of stoichiometric (Ref. 8). Ignition temperature ranges from 1544 to 1752°R, depending on particle size. These values indicate that aluminum powder reactions are similar to hydrocarbon reactions.

An experimental investigation to determine the performance and operating characteristics of two aluminum-air combustors was carried out by NASA prior to 1951 (Ref. 9). One combustor evolved and studied by NASA burned 3/16-in.-diam aluminum wire. A flameholder was not required. Operation of this combustor was stable over a range of fuel-air ratios from 0.31 to 0.92 of stoichiometric with a combustor air inlet velocity of 115 ft/sec. Combustion efficiency was between 70 and 80 percent over the full range of operation. A sketch of the wire atomizer and inlet section used in the NACA experiment is shown in Fig. 1. The combustor is shown in Fig. 2.

Performance achieved in the NACA experiments would be adequate for a wind tunnel combustion air heater. Combustion efficiency was high for aluminum/air ratios of 0.07 to 0.2 in the NASA experiments. Aluminum/air ratios required for a wind tunnel heater producing air temperatures of 4100°R would be around 0.077. The liquid aluminum in the tunnel working fluid due to incomplete combustion in the heater might be a problem. Superior performance could probably be achieved in an aluminum-oxygen combustor.

Operating limits of the NACA aluminum-wire combustor would permit variations in wind tunnel air temperatures over a wide range. Tunnel air temperature could be varied by changing the speed at which the aluminum wire is fed into the combustor. The macroscopic combustion characteristics of aluminum are shown in the NACA experiments to be compatible

with wind tunnel heater requirements. That is, acceptable combustion efficiencies could be obtained over a sufficiently broad aluminum/air ratio with stable combustion, and energy release rate of the heater can be easily varied.

Additional experimental research and development would be necessary to evolve an aluminum-oxygen or aluminum-oxygen enriched air combustor for a wind tunnel air heater. Such investigations should be aimed at achieving high combustion efficiencies, wide stable operating limits, mechanical integrity, and large combustion-product particles. Studies of the macroscopic combustion properties of other fuels listed in Table 1 should be made, provided the fuels are not eliminated by considerations of thermodynamics, availability, cost, or microscopic combustion characteristics.

Combustion of aluminum with oxygen produces Al_2O_3, which is less volatile than aluminum. Aluminum burns on the surface. The oxide formed by combustion of a given amount of aluminum occupies a greater volume than the volume occupied by the aluminum used in forming the oxide. The surface combustion and the relatively greater volume of the oxide of aluminum result in the formation of a protective layer of oxide on a particle of aluminum that is burning in oxygen (Ref. 10). This microscopic combustion property offers a possible means of controlling the particle size in the exhaust products from an aluminum combustor. Large combustion product particle size will make the problem of separating the aluminum oxide particles from the air easier.

A study of the microscopic combustion properties of the other nine fuels listed in Table 1 should be conducted.

2.4 OXIDE REMOVAL

Drag and heat-transfer data obtained in a wind tunnel are compromised by the presence of solid contaminants (Ref. 11). Oxide particles from a combustion air heater may affect ramjet combustor data obtained in a wind tunnel. Removal of the metal-oxide particles from the wind tunnel air supply will probably be necessary.

Metal-oxide separation from the air of a wind tunnel air supply system by means of high-speed oxide-particle injection, electrostatic forces, gravitational forces, and centrifugal forces were studied.

Centrifugal forces proved to be the only means, of those considered, that could be used to separate the aluminum-oxide particles from the air.

A possible configuration for centrifugal separation is shown in Fig. 3. It was assumed that the aluminum-oxide particles were injected at a velocity equal in magnitude and direction to that of the air. If drag forces were not present the acceleration of the particle with respect to the center of the duct in a radial direction would be U^2/R.

This radial acceleration can be related to a hypothetical force

$$F_C = \frac{m}{g_c} \frac{U^2}{R}$$

The drag force acting on the particle is according to Stokes' law

$$F_D = 6\pi r \mu V$$

These forces and Newton's First Law give an equation for the motion of the particle in the plane normal to the duct centerline:

$$F_C - F_D = \frac{m}{g_c} \frac{dV}{dt}$$

Combining and rearranging resulted in

$$C_2 \; dt = \frac{dV}{-V + \frac{C_1}{C_2}}$$

where

$$C_1 = \frac{U^2}{R} = 10{,}000$$

$$C_2 = \frac{18 g_c \mu}{4 \rho_{Al_2O_3} r^2} = 14{,}160$$

The numerical values given are for a radius of rotation of 4 ft, a tangential velocity, U, of 200 ft/sec, particle radius, r, of 2.5 microns, and viscosity of air at a temperature of 4100°R and a pressure of 100 atm. Integration and rearranging,

$$V = \frac{C_1}{C_2} - e^{\left[\log_e \frac{C_1}{C_2} - C_2 t\right]} = \frac{C_1}{C_2}\left[1 - e^{-C_2 t}\right]$$

The exponential decay function in this equation can be ignored because it introduces an error of less than one percent for particle diameters of 5 to 50 microns considered in this analysis. Neglecting the exponential decay function results in a constant radial velocity of

$$V = \frac{C_1}{C_2}$$

and the radial distance traveled by the particle is

$$S = Vt = \frac{C_1}{C_2} t$$

A rotational velocity, U, of 200 ft/sec was assumed, and a mean radius of rotation of 4 ft was used along with a particle diameter of 5 microns in numerical calculations.

$$S = \frac{10^4}{14.160} t = 0.706 \, t$$

For

$$S = 1 \text{ ft (Fig. 3)}$$

$$t = \frac{S}{0.706} = \frac{1}{0.706} = 1.416 \text{ sec}$$

Inspection of the expression for C_2 shows that if it were possible to increase the particle diameter to 50 microns, the radial velocity would increase by a factor of 100. The time required for a particle to travel one foot radially would decrease to 0.014 sec. An empirical equation based on experimental data that would provide a more conservative separation time for the larger particles is given in Ref. 12. Electronic computer calculations would be required to obtain solutions of the empirical equation for the larger particles, and this is left for a detailed design analysis.

The separator should be as short as possible to avoid thermal losses. A facility airflow of 500 lb/sec through the separator configuration shown in Fig. 3 would require an air velocity parallel to the duct centerline of

$$w = \frac{m_a / t}{A \rho_a}$$

$$w = \frac{500}{\left[\frac{1}{13} \; \frac{100}{1} \; \frac{520}{4100} \; \frac{\pi}{4} \; (81-49)\right]} = 24 \text{ ft/sec}$$

Length of the separator for separation of 5-micron particles would be

$$S = wt = 24 \times 1.416 = 34 \text{ ft}$$

Length of the separator for 50-micron particles would be 0.34 ft.

Total pressure loss incurred in establishing and removing the rotational velocity in the separator would increase the cost of a facility compressor system or decrease the air supply pressure. It was assumed that the dynamic pressure required to produce the rotational velocity was lost. The compressible flow equation was used to obtain the relationship

$$\frac{P}{p} = \left[\frac{U^2}{2 J g_c C_p T} + 1\right]^{\frac{\gamma}{\gamma - 1}}$$

The rotational velocity of 200 ft/sec used in the numerical calculations on the centrifugal separator results in a pressure ratio of

$$\frac{P}{p} = (1.00274)^{3.67} = 1.01$$

Thus for an air supply pressure of 100 atm, the pressure loss in the separator would be 1 atm.

Results of this analysis indicate that it may be possible to remove aluminum-oxide particles generated in a combustion heater from the air supply system of a wind tunnel. The calculations show the need to attempt to obtain large oxide particles from the combustor. Experiments should be undertaken to verify the analysis of the oxide removal system and to determine the amount of air which must be bled off the air supply duct to carry the aluminum-oxide particles. Analysis and experiments should also be undertaken to determine if valid test data can be obtained with aluminum-oxide particles in the airstream. Analytical and experimental studies of separation of oxides of some of the other fuels listed in Table 1 from a wind tunnel air supply system should be undertaken.

2.5 HEAT TRANSFER FROM METAL OXIDE TO AIR

Proper design of the metal-oxygen combustor and the use of air film cooling to protect the burner structure should result in liquid metal-oxide particles flowing from the burner outlet into the airstream in a wind tunnel air supply system. Thermal energy of these metal-oxide particles must be transferred to the air.

Eckert and Drake (Ref. 13) give the empirical relation for heat-transfer coefficients for spheres:

$$Nu = 2 + 0.37 \, |Re|^{0.6} \, |Pr|^{1/3}$$

The configuration shown in Fig. 3 with rotational velocities of 200 ft/sec results in relative velocities between the oxide particles and the air of 0.706 ft/sec for particles 5 microns in diameter.

Reynolds number under the assumed conditions in the separator is 0.253 for 5-micron particles. Prandtl number is 0.767 (Ref. 14), and the resulting value for Nusselt number is 2.144. Surface heat-transfer coefficient is

$$q = \frac{Nu \, k_a}{d} = 1.794 \; \frac{Btu/ft^2}{sec \; ^{\circ}R}$$

for the 5-micron particles.

Schneider (Ref. 15) gives for the rate of thermal energy transfer in Newtonian heat transfer

$$\frac{Q}{Qi} = 1 - e^{-3 \, Nu \, \theta}$$

where

$$Nu = q\ r/k_{Al_2O_3}$$

$$\theta = k_{Al_2O_3}\, t/C_{p_{Al_2O_3}}\, \rho_{Al_2O_3}\, r^2$$

The time required for 95 percent of the thermal energy of the 5-micron particle to be transferred to the air is, from the above expression,

$$t = \frac{\log_e 20\ C_p\ \rho\ r}{3\ q} = 0.0005 \text{ sec}$$

These same relationships were used to determine the time required for transfer of 95 percent of the energy of a 50-micron-diameter particle to air in the separator. Time required for the energy transfer from the 50-micron particle was 0.0041 sec.

Time required for thermal energy transfer is less than one third the time required for separation of the 50-micron particles. Time required for thermal energy transfer is more than three orders of magnitude less than time required for separation of the 5-micron particles. Thus residence time of the molten oxide particles in a feasible separator is sufficient for energy transfer to take place. The relatively small residence time needed for complete energy transfer compared to the time required for separation of the oxide particles from the air indicates the possibility of achieving higher air temperatures by using only the air from the innermost annulus of the heater as working fluid in a wind tunnel. Conversely this property of the heat-transfer and separation processes could result in relatively low temperature air and oxide being bled off the separator when mean air temperatures into the wind tunnel are held to 4100°R. Simplification of the bleed system design and minimization of thermal losses could be achieved by use of this latter heater design philosophy.

The relationship between particle size, separation time, and thermal energy transfer time discussed above are typical. That is, the very small particles transfer their thermal energy to the surrounding gases very rapidly. Particle density and specific heat are factors in the relationship between separation time and thermal energy transfer time, and thus specific data on particles other than aluminum oxide would require that these calculations be repeated for other candidate fuels.

2.6 CONSTRUCTION AND OPERATING COSTS

The preceding analysis seemed to validate feasibility of combustion air heaters that provide clean air. The analysis did show that an experimental investigation to check the assumptions would be warranted.

Economic factors were studied in order to determine the magnitude of experimental effort on this heater concept that is warranted. Estimated construction cost of a heater such as that shown in Fig. 3 along with the estimated construction cost of a ceramic pebble bed heater is given in Table 2. The combustion heater cost is less than one-half the cost of a ceramic pebble bed heater that has a considerably shorter run time. Included are the heater, separator, and auxiliaries with insulation and cooling systems for run times of thirty minutes. Estimates are for a heater having an airflow rate of 500 lb/sec and an outlet air temperature of 4100°R. Cost of the ceramic pebble bed heater with the same performance but more limited operating capability was based on estimates furnished to AEDC by FluiDyne Corporation. These estimates assumed advances in the state-of-the-art of pebble bed heater design and fabrication over those now in operation. A run time of thirty minutes would require installing ten of these systems in parallel, with a total cost in the neighborhood of thirty million dollars.

Operating costs of the combustion air heater were based on a combustion efficiency of 70 percent. Aluminum consumption of the heater was calculated from the following equation:

$$w_{Al} = w_a \times \frac{w_{Al}}{w_a} \times \frac{1}{\eta} = 500 \times 0.077 \times \frac{1}{0.7} = 55 \text{ lb/sec}$$

Cost of 1/4-in.-OD, ninety-nine percent pure aluminum wire is quoted at \$0.451/lb by Aluminum Company of America. Cost of 1/16-in.-OD wire is \$0.555/lb. Oxygen consumption of the heater was calculated by use of the following equation:

$$w_{O_2} = w_a \times \frac{w_{O_2}}{w_a} = 500 \times 0.0684 = 34.2 \text{ lb/sec}$$

The current price of liquid oxygen at AEDC is \$0.0242/lb.

Estimated cost for maintenance and operating expenses of \$80,000 per year was based on experience at AEDC in operating equipment of comparable size and complexity. An assumed heater utilization of sixty-six hours per year yields a cost of \$20.00 per minute for maintenance and operating costs other than fuel and liquid oxygen. Total cost of operation per minute of run time for the combustion air heater is \$1,900.

Estimates of pebble bed heater operating cost are difficult to analyze. Only a small portion of the thermal energy put into the ceramic material can be removed during a useful run. Efficiency of the heater will therefore be greatly influenced by design variables as well as operating procedures. Actual pebble bed heater costs were obtained from firms using such heaters. Present-day zirconia heaters with outlet temperatures in

the neighborhood of 4100°R have operating costs of $100 per pound per second of air flow for a one-minute run. Present-day alumina heaters with outlet temperatures in the neighborhood of 2500°R have operating costs of $2.00 per pound per second of airflow for a one minute run. Sixty percent of the cost of operation of the zirconia heaters represents cost of replacement ceramics. New designs and new materials now being developed may lower the cost of operation to $10 per pound per second of airflow for a one-minute run. This figure yields an operation cost of a 500-lb/sec air heater of $5,000 per minute.

Estimated construction and operating costs of the non-contamination combustion air heater were much less than the corresponding costs of an equivalent pebble bed heater. It was concluded from the cost differences that an experimental research effort on the non-contaminating combustion heater concept on the order of $100,000 would be reasonable.

3.0 SUMMARY OF RESULTS

An analysis of a non-contamination combustion air heater that is capable of raising the temperature of 500 lb/sec of air to a temperature of 4100°R at a pressure of 100 atm showed that:

1. Combustion of aluminum with oxygen at an aluminum-to-air weight ratio of 0.077 lb/lb is required to provide the energy to heat the air from 1200 to 4100°R.

2. Reaction rates of aluminum with air, the combustion efficiency, and the stable operating limits of an aluminum-air burner tested by NACA in 1950 are compatible with wind tunnel heater requirements.

3. Microscopic combustion properties of aluminum and oxygen may permit control of the aluminum-oxide particle size through variation of burner design parameters.

4. Centrifugal separators 34 ft long with tangential velocities of 200 ~~lb~~ ft/sec remove 5-micron aluminum-oxide particles from air at a pressure of 100 atm and a temperature of 4100°R.

5. Estimated construction and operating costs of a non-contaminating combustion air heater are lower than for a zirconia pebble bed sotrage heater with equivalent performance and operating capability.

6. Additional theoretical studies should be made of the possibility of achieving air temperatures above 5000°R by using magnesium, hafnium, thorium, or zirconium as a fuel.

7. Experimental investigations of such a heater should have as their objectives:

   a. To study particle interaction effects on the particle separation and to determine the amount of bleed air required to transport the aluminum-oxide particles out of the separator.

   b. To develop an aluminum-oxygen burner having performance and operating characteristics compatible with wind tunnel heater requirements, giving special attention to maximizing oxide particle size from the burner.

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TABLE 1

FUELS FOR WIND TUNNEL COMBUSTION AIR HEATER THAT PRODUCE COMBUSTION PRODUCTS WITH HIGH MELTING TEMPERATURE

Fuel	Oxide Formula	Oxide Melting Temperature, °R
Aluminum	Al_2O_3	4184
Magnesium	MgO	4992
Metazirconate	$CaZrO_3$	5081
Chromium	Cr_2O_3	4078
Hafnium	HfO_2	5550
Lanthanum	LO_2S_3	4273
Thorium	ThO_2	5530
Titanium	Ti_2O_3	4328
Yttrium	Y_2O_3	4830
Zirconium	ZrO_2	5350

TABLE 2

ESTIMATED COST OF NON-CONTAMINATING COMBUSTION AIR HEATER AND CERAMIC PEBBLE BED HEATER

Combustion Heater Costs	
Shell	$ 634,000
Inlet Swirl Vanes	16,000
Trailing Egg Crate	26,000
Center Body	194,000
LO_2 System (30-min Run at an Airflow of 500 lb/sec)	18,000
Aluminum Feed System	50,000
Propane Start System	10,000
High Press. Transpiration Cooling	25,000
Low Press. Water Cooling	20,000
Al_2O_3 Washer and Stack	50,000
Instrumentation	50,000
Foundations	35,000
Ignition System	3,000
15-percent Contingencies and 8-percent C of E	264,000
TOTAL	$1,360,000
Ceramic Pebble Bed Heater Costs	
Airflow of 500 lb/sec for 3 min	$3,000,000

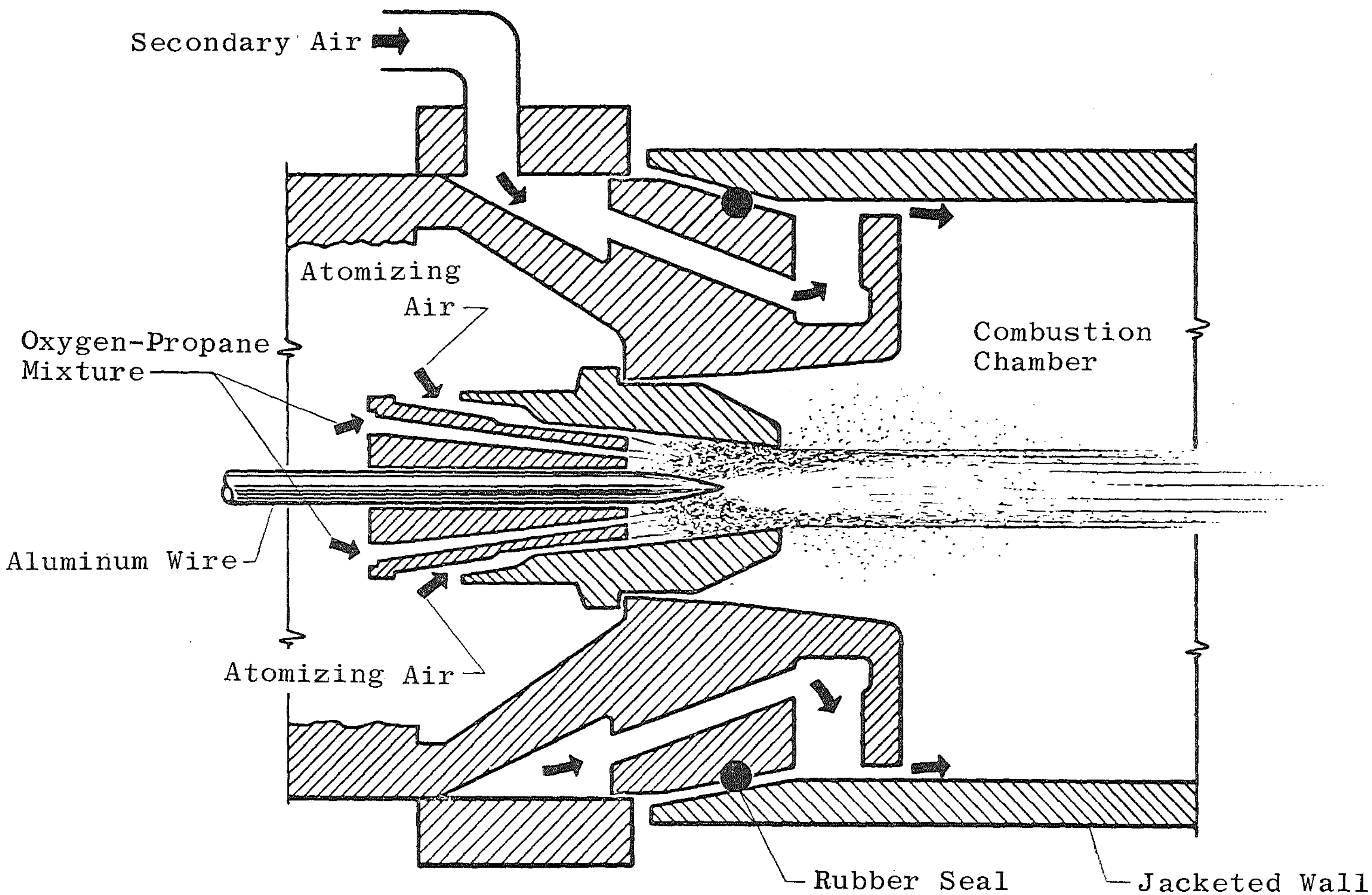

Fig. 1 Cross-Sectional View of Wire Atomizer

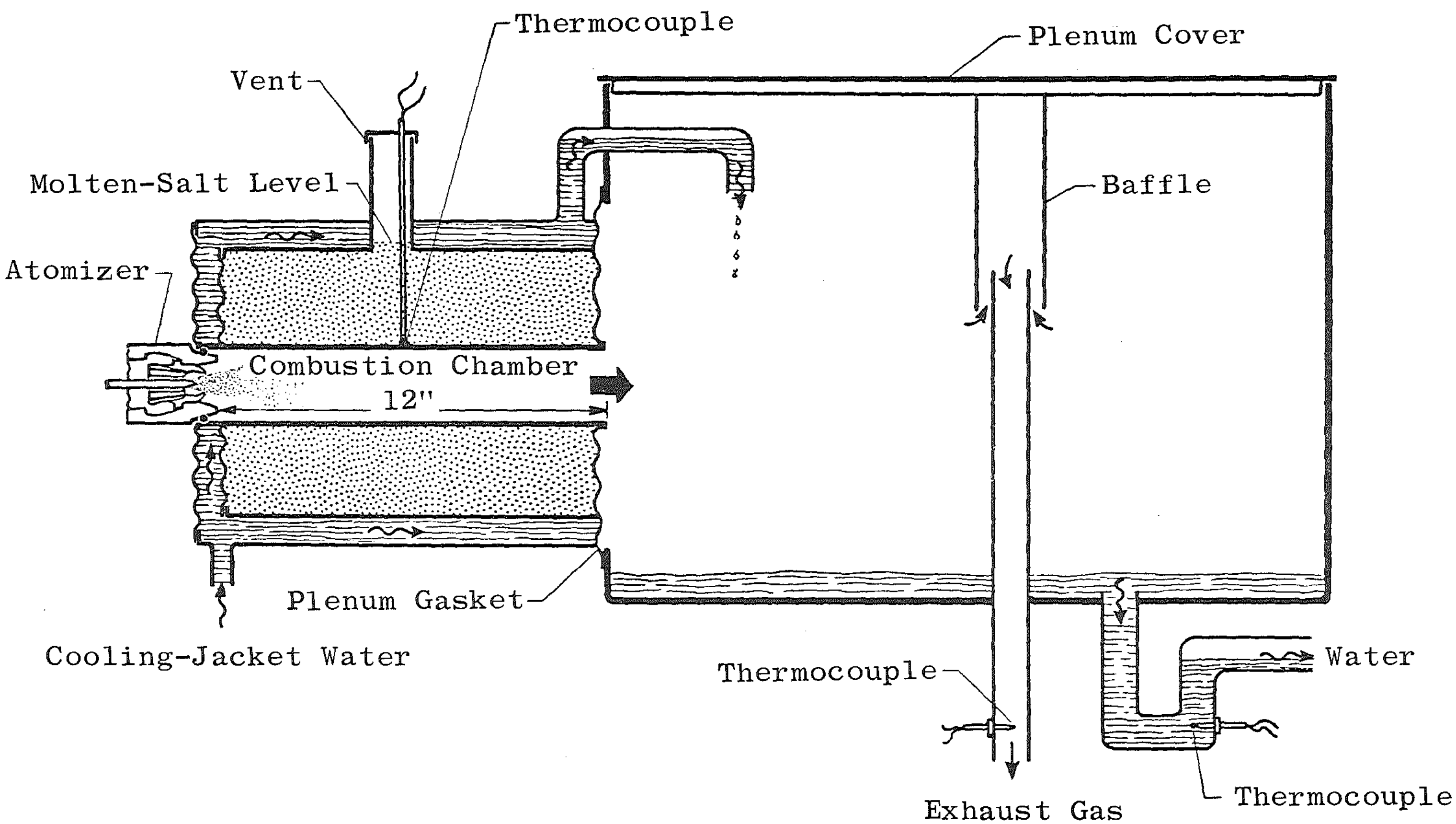

Fig. 2 Combustor and Plenum Chamber

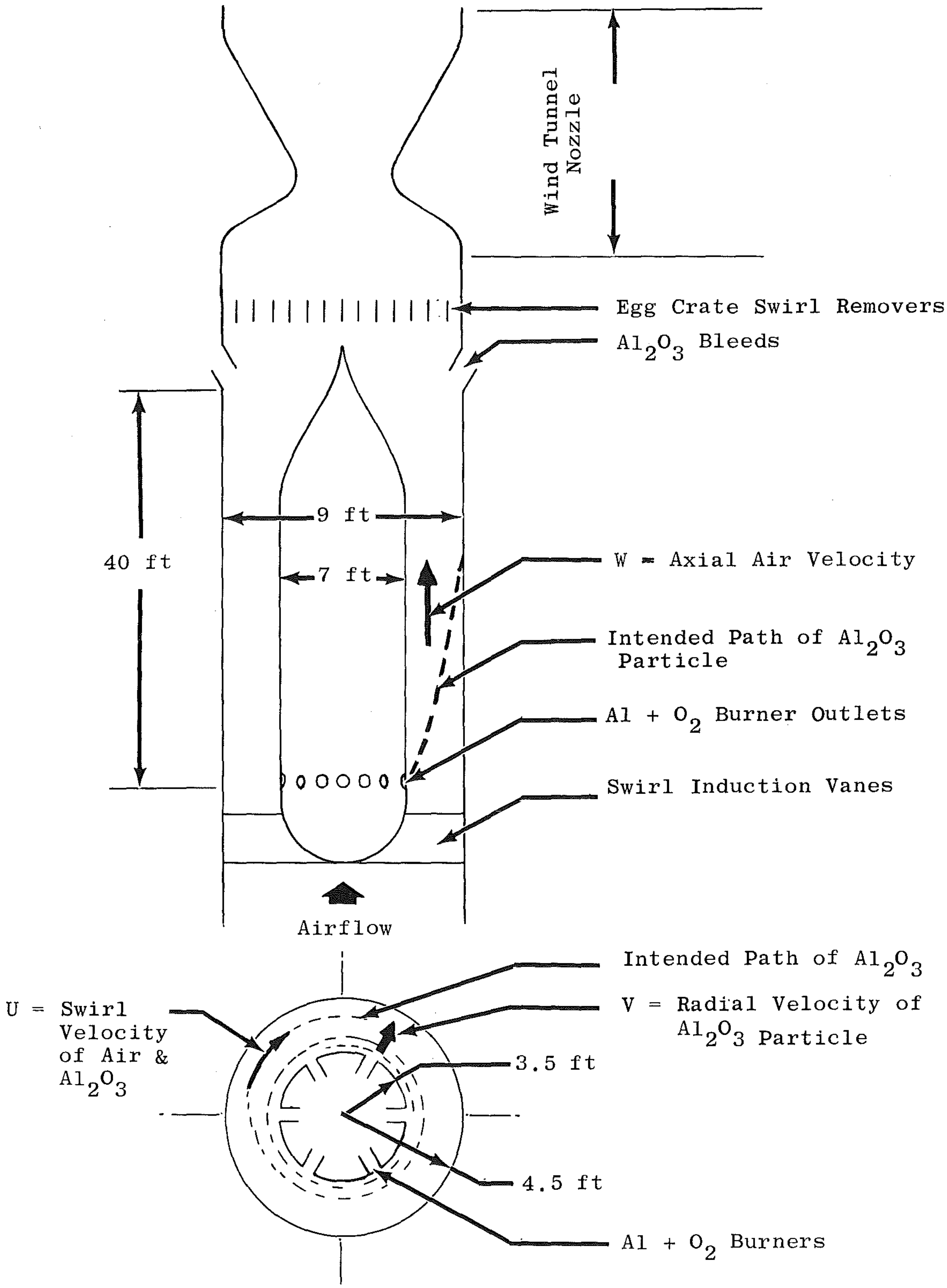

Fig. 3 Possible Configuration for Centrifugal Separation of Al_2O_3 from Air